Proceedings of the 3rd Croatian Conference on Earthquake Engineering - 3CroCEE
19–22 March 2025, Split, Croatia

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.70

INTEGRATED NON-DESTRUCTIVE APPROACH FOR THE DIAGNOSIS OF HISTORIC MONUMENTS

Jasna Grujoska-Kuneska(1), Veronika Shendova(2)

[1] *PhD student, Institute of Earthquake Engineering and Engineering Seismology-Skopje, jasnagrujoska@yahoo.com*
[2] *Professor, Institute of Earthquake Engineering and Engineering Seismology-Skopje, veronika@iziis.ukim.edu.mk*

Abstract

As part of the tangible cultural heritage, historic buildings hold great importance for today's societies. These are buildings that have persisted for hundreds or thousands of years as visible witnesses of the past generations and their traditions, and as such deserve special attention and treatment.

A particular challenge is the protection of historical buildings located in seismic regions, where in addition to the climatic and human factors, these buildings are exposed to the effects of earthquakes, and so despite their visually good condition they exist today with many hidden weaknesses. Historic buildings respond to earthquakes, among other things, depend on the correct treatment and conservation practice. In order to achieve all that, a solid diagnostic study that will ensure an accurate assessment of its current condition is an essential prerequisite.

This paper presents the non-invasive methodology carried out to one Byzantine monument – the church of St. Nikita near Skopje, North Macedonia, using the available Non-Destructive Techniques (NDTs): visual inspections, microscopy, infrared thermography, 3D laser scanning and ambient vibration tests. The use of the above mentioned NDTs enabled to evaluate the current condition of the monument in a relatively short time without affecting its authenticity, which is especially significant for this type of buildings. Additionally, the use of the 3D laser scanner generated digital documentation of the monument, accessible at any time.

Keywords: tangible heritage, byzantine churches, conservation, diagnostic study, non-destructive techniques, digital documentation

1. Introduction

Cultural heritage, both tangible and intangible, holds great importance in today's societies, acting like a bridge that connects us to the past. It promotes our identity and can contribute to economic development, poverty reduction and sustainable development, [1].

Significant part of the cultural heritage in North Macedonia consists of historic buildings from different periods, which symbolize diverse cultures and people who lived before. Byzantine churches are among the most preserved and numerous monuments characterized by exceptional architectural and artistic values. These medieval monuments range from monumental basilica-type churches, conch and domed square-in-plane concepts, to small single nave churches, [2][3].

Many factors, such as urbanization, excessive tourism, climate changes, people's neglect and loss of traditional knowledge, affects this tangible heritage. Additionally, the vulnerability of historic buildings is greater in seismic prone regions as earthquakes pose a big treat to the stability of the buildings and may cause irreversible damage, [4].

The earthquake that struck Skopje in 1963 is one of the biggest natural disasters in the recent history of North Macedonia. With magnitude of 6.1 degrees (Richter scale) the earthquake caused minor to major damage to all cultural-historical buildings in Skopje and nearby. The buildings located in the old bazaar, dating from different periods (churches, mosques, baths, shops) were significantly damaged. Many Ottoman buildings (15^{th}-16^{th} centuries) were affected and few were almost entirely destroyed. The Byzantine churches (9th-14th centuries) also suffered some damages, [5].

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.70

Even with the technological advancements we cannot predict earthquakes, neither to reduce their intensity, [4] but what we can do is to take preventive measures to reduce the vulnerability and potential damages to the heritage buildings. The seismic performance of these buildings depends on many aspects, including the correct and professional treatment and conservation practice. In that perception, the diagnostic study that provides an accurate assessment on the building's condition and consequently suitable conservation measures is imposed as vital step in the long-term process of heritage protection, [6].

2. Representative Byzantine monument: St. Nikita church

The church of St. Nikita is a typical late Byzantine monument from 14th century with exceptional architectural, artistic and historic values. It is located outside the city of Skopje, on the slopes of Skopska Crna Gora in the village of Banjani. Typologically, the church belongs to group cross-in-square plans with a single-dome, which is one of the most common typology in the country. The church contains two main clearly defined units: the central naos and an altar area, without narthex. Structural system consists of massive facade walls and columns (in the interior) that support the vaulted roof elements and the central dome. Different types of stones (mainly limestone and sandstone), bricks and lime mortar were used in the construction of the building. Special attention is paid to the construction of the facades, using three dimensional polychrome, shallow niches and pilasters, (fig. 2.1). The pentagonal apse, on the east side, is visually enriched with double niches with brick arches. The interior surfaces of the church are plastered and painted with frescoes, preserved on a larger scale, (fig. 2.2). The original frescoes, from 14th century, symbolize the rich artistic Byzantine life which adds up to the artistic values of the monument, [2][7].

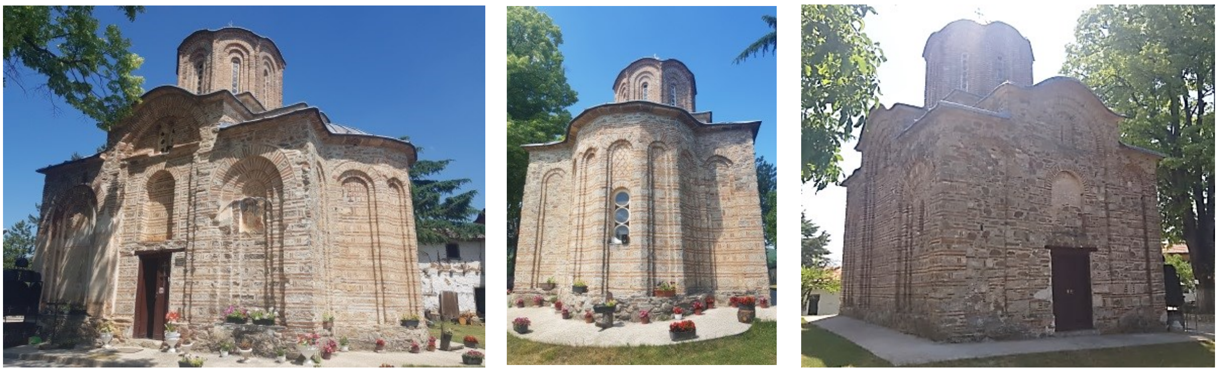


Figure 2.1 Facades of St. Nikita church

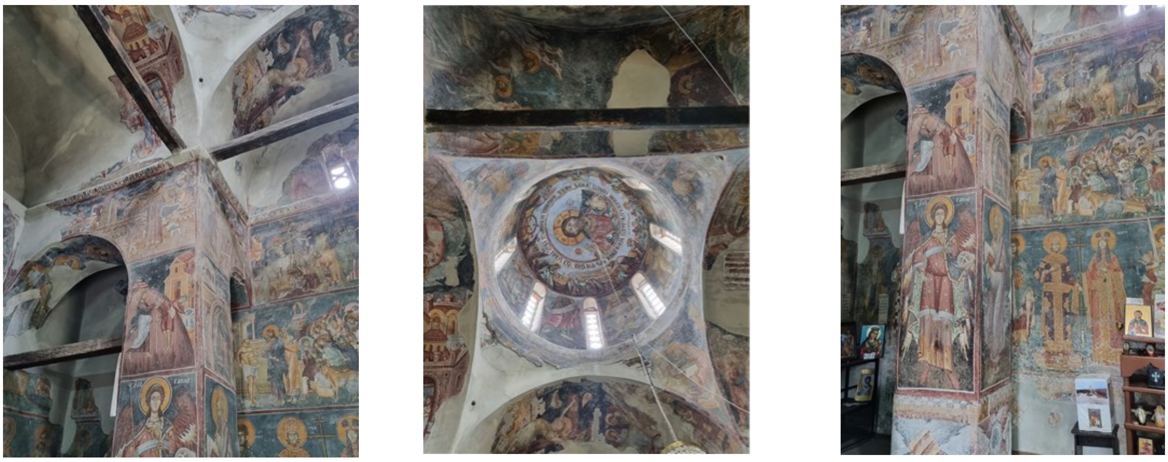


Figure 2.2 Interior of St. Nikita church

Proceedings of the 3rd Croatian Conference on Earthquake Engineering - 3CroCEE
19–22 March 2025, Split, Croatia

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.70

3. Diagnostic study on St. Nikita church

For the selected monument an integrated diagnostic study was carried out to assess its existing state. This study included different phases – archival research, documents review, field surveys and recording. The archival research and the review of the existing documentation enabled insight into the different historical stages of the building and previous interventions, (table 3.1).

Table 3.1 Review of historical changes on St. Nikita church, [7][8][9]

1307	The church was built on the base of an older building from XI or XII century
Ottoman period	Addition of small single nave structure on the south side of the church (demolished in 1928)
XIX century	Reconstruction activities on the dome of the church addition of a closed porch on the south and west side (demolished in 1928)
1963 (Skopje earthquake)	Damages in the interior of the church in form of cracks and detachments of the frescoes
1967	Conservation activities on the frescoes in the interior
1968	Conservation activities on the architecture
1978-80	Extensive intervention on the roof parts: restoration of the roof and replacement of the roof tiles with a lead sheet

During the field survey the monument's condition was assessed using the available non-destructive techniques: visual inspections assisted by drone, digital microscopy, infrared thermography, 3D laser scanning and ambient vibration tests.

3.1 Visual inspections assisted by drone

The visual inspections were conducted on the facades of the church and on the inside, and provided information regarding the visible surface irregularities and damage. Inspections on the facades pointed to certain irregularities, such as evident porosity of the limestone and carbonization of the lime mortar; presence of capillary moisture in the lower zones of the northern and western walls; presence of lichens in the lower and middle zones on each facade, (fig. 3.1). However, the general condition of the facades was assesses as relatively good and preserved, without the presence of major damages that could pose a further threat to the monument.

Figure 3.1 Surface irregularities on the facades of St. Nikita church: porosity on limestone (left), presence of moisture (middle), presence of lichens (right)

Proceedings of the 3rd Croatian Conference on Earthquake Engineering - 3CroCEE
19–22 March 2025, Split, Croatia

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.70

The interior of the church is completely plastered and covered with frescoes, preserved on a larger scale; therefore the condition of the structure materials cannot be investigated. Fine cracks were observed in several spots of the upper zones in the walls and vaults. It was also noticed that one of the wooden ties was disrupted, (fig. 3.2).

Figure 3.2 Damage in the upper zones of the church

Use of the drone enabled to investigate some challenging areas that were difficult to access during visual inspections. The high-quality photographs from an aerial perspective presented the wider context of the church within the surrounding and also provided an opportunity to investigate the roof's covering. The lead sheet (cover material) is well preserved, apart from the segment of the dome (fig. 3.3 right) where some cracks were noticed, probably due to unprofessional fixing of the joints.

Figure 3.3 Aerial perspectives of the church

3.2 Digital microscopy

The images from the microscope (magnification 40x) allowed more detailed view of the different types of lichen that are present on the facades of the church, (fig. 3.4). The presence of the lichens can be correlated to some minor micro cracks on the facades, but had not significantly affected the condition of the materials. Additionally, most of the lichens form kind of crust that firmly attach to the substrate; therefore their mechanical removal on large areas is particularly difficult and could damage the original materials. So, at this point, removing the lichens would cause more damage than benefits.

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.70

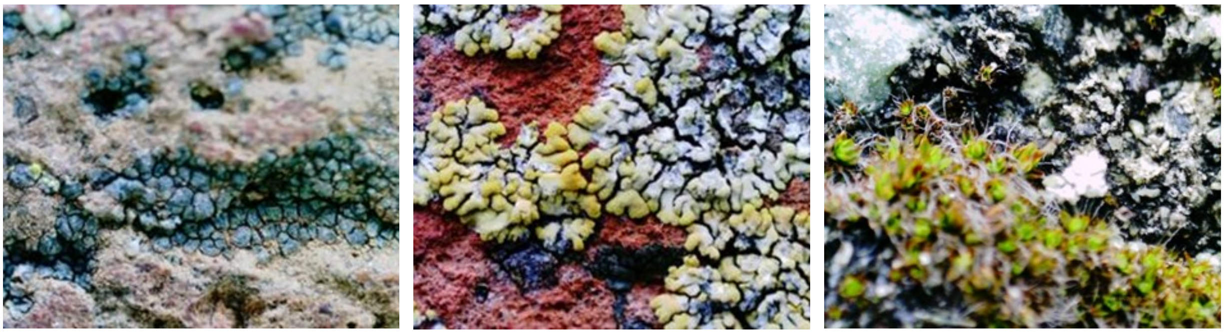


Figure 3.4 Different types of lichens present on the facades of the church (magnification 40x)

3.3 Infrared thermography

Infrared thermography is an evaluation technique that uses a thermal imaging camera to records the infrared radiation emitted by materials as a result of natural heating or cooling process and to correlate these variations to material's condition and properties, [10][11]. The thermal imaging surveys on the church of St. Nikita enabled to investigate large areas of the facades and the interior of the church.

On the facades, the technique was used to detect the distribution of moisture within the walls. Thermal image (fig. 3.5) shows irregular shapes of thermal anomalies, characteristic for the presence of moisture. The lower zones, which are actually the moisture zones, show lower temperatures (presented with blue and yellow colors) compared to the rest of facade surface. The moisture is mainly present at the contact zone between the wall and the sidewalk and rises up to 60-80cm of the wall's height.

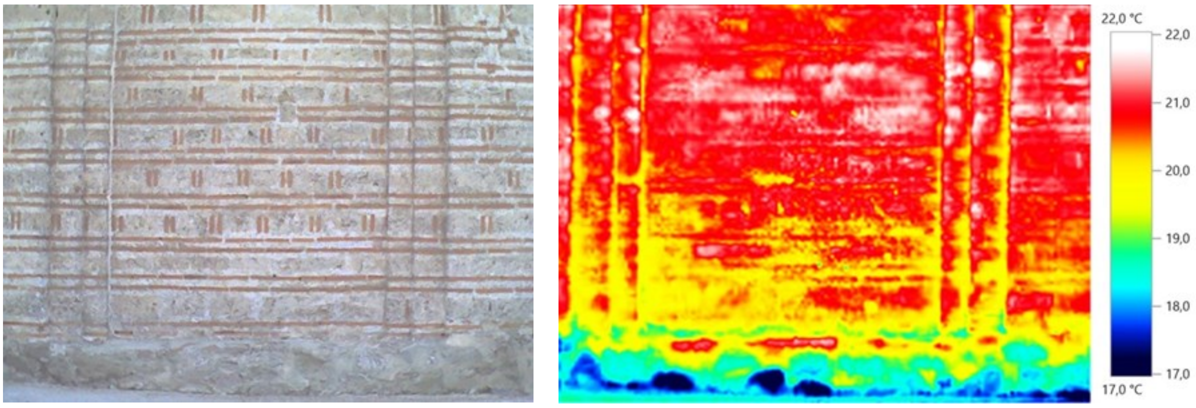


Figure 3.5 Segment of the north facade wall of St. Nikita church and corresponding thermal image

In the interior, the technique enabled to investigate the frescoes in a non-destructive way, which is important because due to their value there is no possibility for sampling. Most of the frescoes in the interior of the church are original, date back from 14th century. In the later periods (15th and 19th century) some of the damaged frescoes have been partially restored and others have been painted on a new layer of plaster. Since the restorer masters have followed the original work, it's difficult to separate the new of the old frescoes, but they vary in their composition and characteristics, and consequently, have different emissive values that can be observed with the thermal camera. Figure 3.6 shows a composition on the southern wall, where no surface changes are visually noticeable. However, the thermal image of this part shows temperature variations, i.e. a zone with a lower temperature (marked with a black circle) which may indicate to different material properties and different period of origin.

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.70

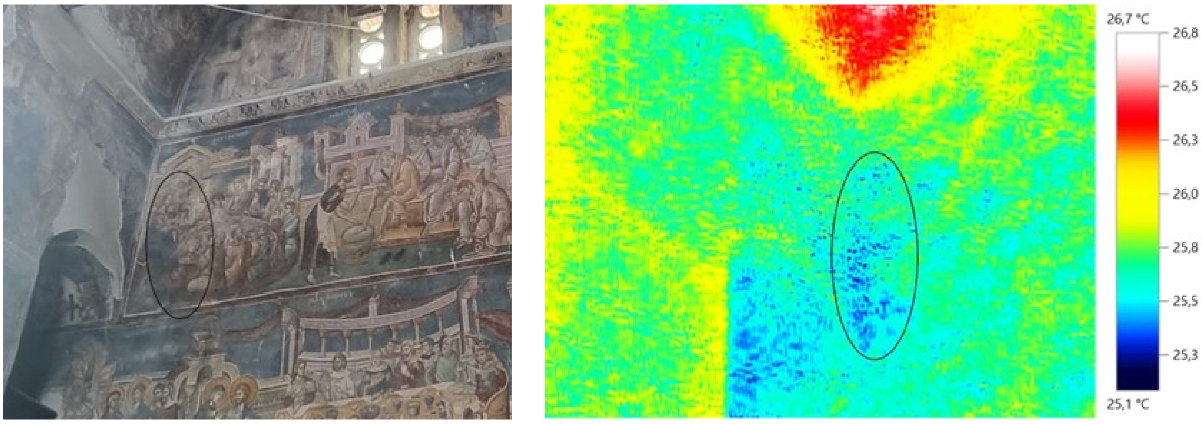


Figure 3.6 Composition on the south wall and corresponding thermal image

3.4 3D Laser Scanning

This is a fast non-invasive acquisition technique that uses laser lights for measuring 3D coordinates of points on surfaces, providing dense point cloud. The point cloud is a collection of millions of points into a common Cartesian (x,y,z) coordinate system that defines the structure's geometry in great detail. The color of the surface at each point can be added to the coordinate and intensity information by the imagery from the embedded camera. Specialized software are used to process the point cloud and create a digital representation of the building, [12].

In the case of St. Nikita church the Leica ScanStation P40 scanner was used, which is one of the latest models of scanners with exceptional precision. The use of the laser scanner enabled to record the entire building and to create a precise 3D model, i.e. a digital replica of the monument, (fig. 3.8). To ensure complete coverage of the building, multiple scans from different angles in the exterior and interior of the church were taken, (fig. 3.7). Combined with the data from the drone recording it gives a complete and precise definition on the building's geometry and structural details.

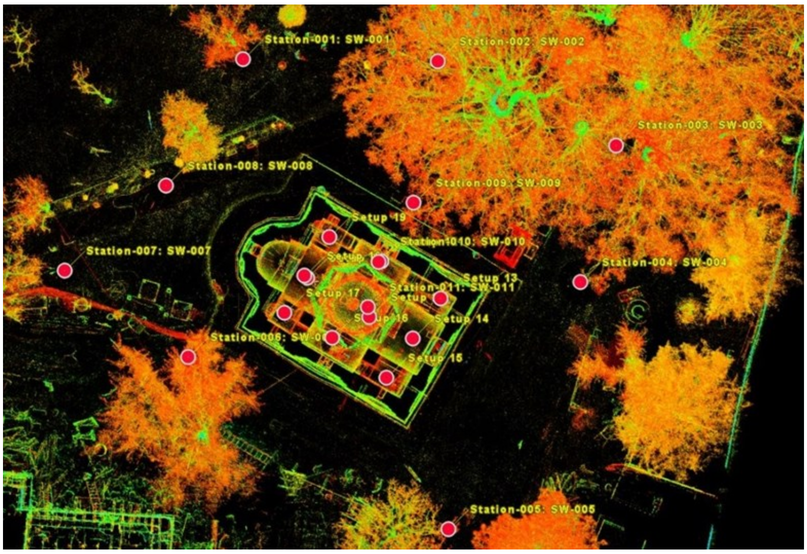


Figure 3.7 Position of the measuring points in the exterior and interior of the church

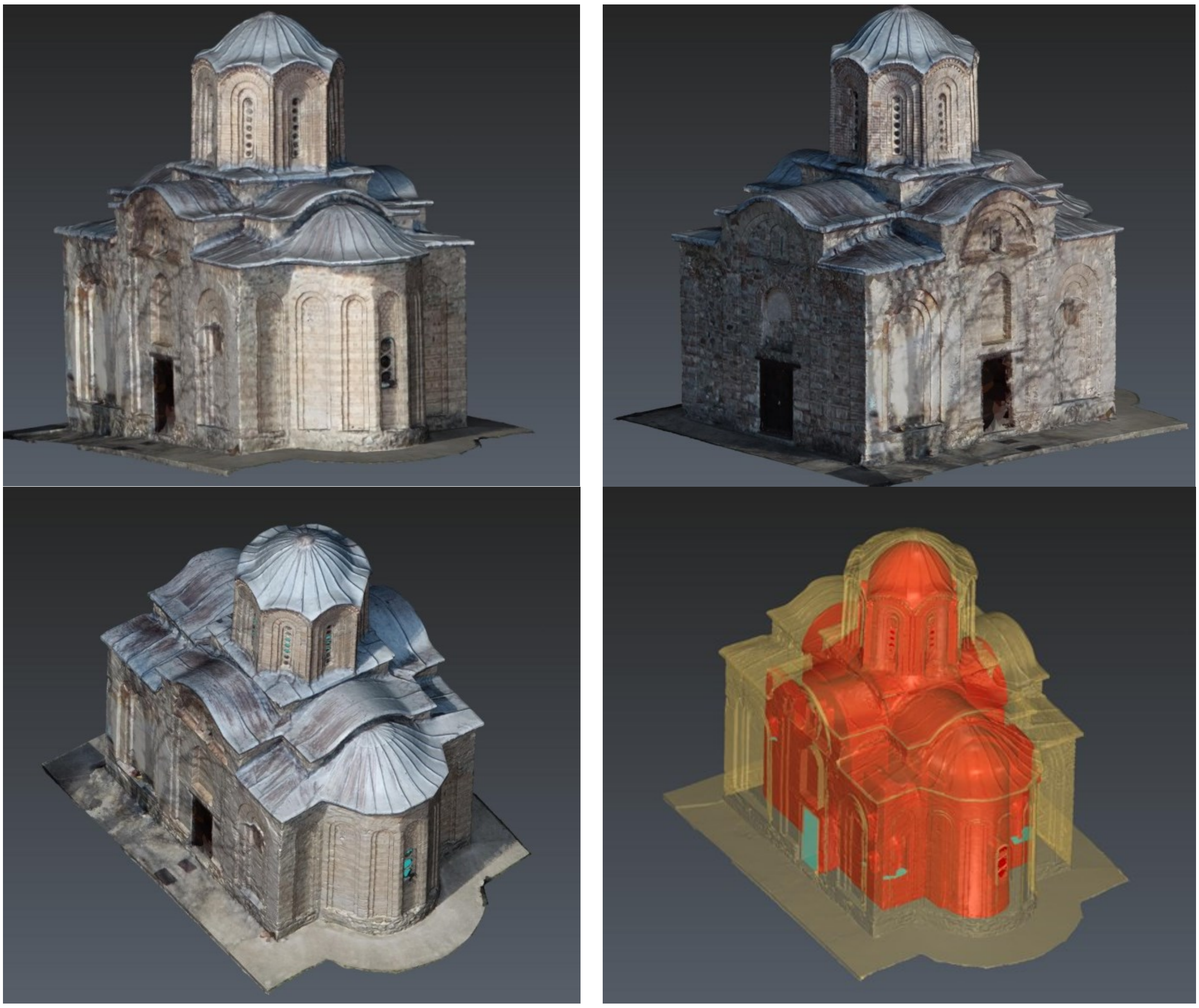


Figure 3.8 Virtual 3D model of the church generated from laser scanning

This 3D model serves as valuable resource for analysis and documentation. It gives opportunity to architects, engineers, conservators and other specialists to visualize and manage building from different angles, regardless the real physical limitations. The precision of the model could be used to measure any dimension of the elements (fig. 3.9) and identify even the smallest details, which facilitated the creation of the mathematical model for further structural analyzes. Additionally, the model was imported into AutoCad program which provided detailed 2D drawings (floor plans) of the building, (fig. 3.10). At this point, all required 2D drawings (section, elevations, floor plans) can be attained and with some additional work they can become valuable digital documentation of the monument, available at any time, without the need for repeated inspection.

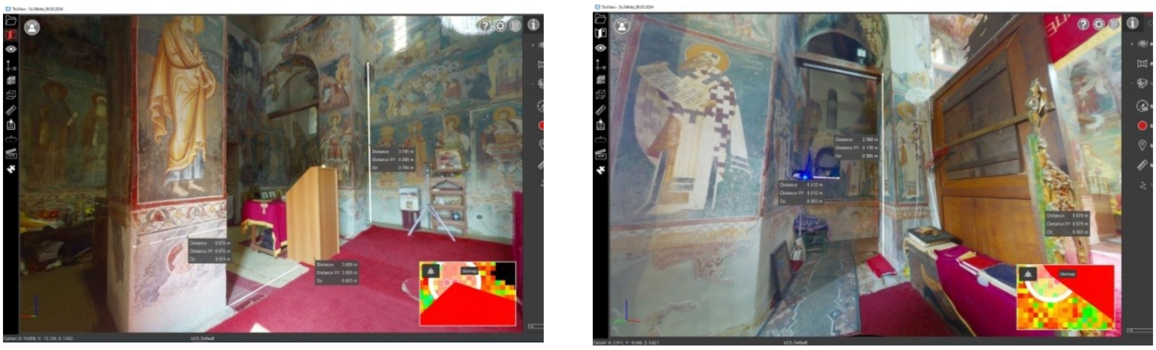


Figure 3.9 Representation of the interior of the church with measurements

This type of information is the basis for monitoring the building's condition and aids the future conservation or restoration processes. Also, it preserves all the physical, historical and cultural aspects of the monument for the future generations.

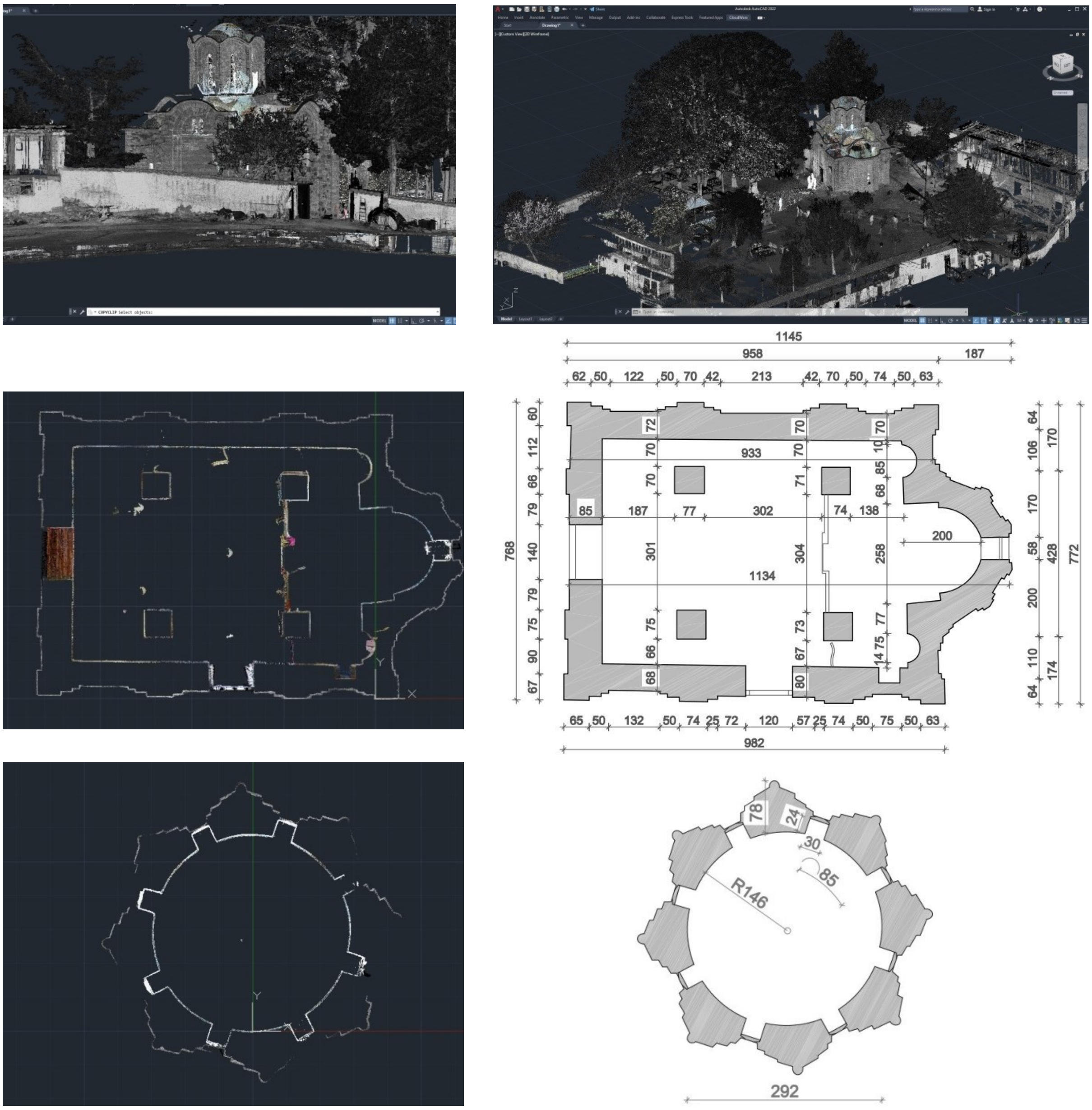


Figure 3.10 3D Model in Cad setting, 2D drawings generated from the model

3.5 Ambient vibration method

This technique has proved to be practical and cost-effective way for the determination of the dynamic properties of the structures, especially suitable in the field of built cultural heritage. The method involves real-time measurements of the small structural vibrations caused by ambient forces like the wind and processing the recorded data, [13].

The dynamic parameters of the structure are related to its physical and mechanical properties like mass, stiffness and energy dissipation, so any major structural change in the system will also be reflected on the dynamic parameters, hence the importance of monitoring. In the case of St. Nikita church, the ambient vibration method was used to determine the dynamic parameters - periods of

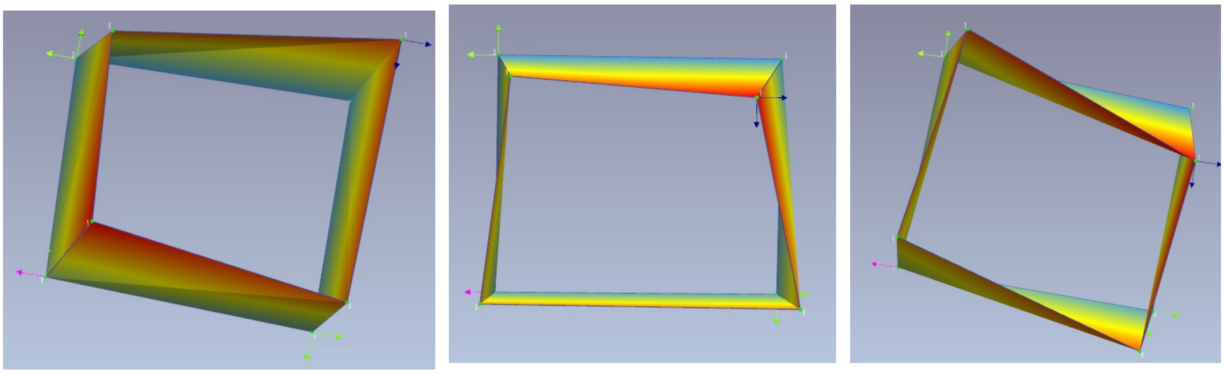
DOI: https://doi.org/10.5592/CO/3CroCEE.2025.70

vibration and mode shapes, [14]. Eight sensitive accelerometers were used with different arrangement and measurement locations at levels 0.00 and +5.40, (fig. 3.11).

Figure 3.11 Positions of the accelerometers

The tests enabled to obtain the natural frequencies in both orthogonal directions: $f_{E\text{-}W}$=5.98Hz and $f_{N\text{-}S}$= 4.70Hz, and sequently the characteristic periods $T_{E\text{-}W}$= 0.167sec $T_{N\text{-}S}$= 0.212sec.

The mode shapes (fig. 3.12) indicate synchronized behavior of the facade walls which contribute to the overall stiffness and stability of the building as one global entity. The displacements in both, longitudinal and transversal directions are generally translational with insignificant presence of rotation more pronounced in the longitudinal direction. Such forms are expected considering the lack of symmetry due to the presence of the semi-circular apse at the altar area.



f=5.98 Hz (longitudinal direction E-W) | f=4.70 Hz (transverse direction N-S) | f=8.05 Hz (torsion)

Fig. 3.12 Frequencies and mode shapes

The results of this research compared to data from similar tests conducted in 1990s -calculated mode shapes were $f_{E\text{-}W}$=6Hz, $f_{N\text{-}S}$=4.8Hz (project "Conservation, rehabilitation and strengthening of Byzantine churches in Macedonia", [2]), indicate that there were no changes in the dynamic parameters of the building's structure in the past 30 years, i.e. the past earthquakes, especially the earthquake of 2016 in Skopje did not cause additional damages to the church's structure.

4. Conclusion

Historic buildings are an integral part of our shared heritage. They serve as a connecting bridges to the past, representing the cultural development of the civilizations. Over the years, these buildings are exposed to many impacts (human, natural, climatic, etc.) so despite the visually good condition they may hold many hidden weaknesses. The buildings located in seismic-prone regions are particularly vulnerable, so the precaution to mitigate potential devastation must exist. The diagnostic study that will provide accurate condition assessment and consequently lead to appropriate conservation activities is an essential part of the long-term process of heritage building protection.

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.70

This paper describes an integrated diagnostic study conducted on a medieval monument in North Macedonia – church of St. Nikita near city of Skopje. The study involved archival research, documents review and in-situ surveys using non-destructive techniques: visual inspections aided by drone, microscopy, infrared thermography, 3D laser scanning and ambient vibration tests. The combination of these techniques provided valuable information regarding visible (surface) and hidden irregularities. The use of drone provided additional information for the less accessible areas of the building (aerial perspective). Furthermore, 3D laser scanning technology proved to be valuable resource for the purpose of heritage digital documentation.

5. References

[1] Stanton-Geddes Z, Soz SA. Promoting Disaster Resilient Cultural Heritage. Washington: Word Bank; 2017.

[2] Gavrilović P, Ginell SW, Shendova V, Šumanov L. Conservation and Seismic Strengthening of Byzantine Churches in Macedonia. Los Angeles: Getty Publications; 2004.

[3] Shendova V. Doctoral dissertation: Seismic strenghtening and repair of Byzantine churches (Сеизмичко зајакнување и санација на Византиски цркви). Institute of Earthquake Engineering and Engineering Seismology, IZIIS, Ss. Cyril and Methodius University in Skopje, 1997.

[4] Feilden B. Conservation of Historic Buildings. 3rd Edition. Oxford; Burlington, MA: Architectural Press; 2003.

[5] RZZSK, Kosicki I. Republic Institute for the Protection of Cultural Monuments Skopje, 1963-1983; 1983.

[6] Grujoska-Kuneska J. Doctoral dissertation: Modern approach in existing state diagnosis of cultural-historical monuments - architectural perspective (Современ пристап во дијагностика на состојбата на културно историски споменици-архитектонска перспектива). Institute of Earthquake Engineering and Engineering Seismology, IZIIS, Skopje, 2024.

[7] Markovic M. St. Nikita near Skopje (Свети Никита код Скопља). Belgrade: Sluzben Glasnik; 2015.

[8] NI Conservation Center - Skopje. Written documentation for the church of St. Nikita. 1978.

[9] NI Conservation Center - Skopje. Record documents. Skopje: 1980.

[10] Moropoulou A, Labropoulos KC, Delegou ET, Karoglou M, Bakolas A. Non-destructive techniques as a tool for the protection of built cultural heritage. Constr Build Mater 2013;48:1222–39. https://doi.org/10.1016/j.conbuildmat.2013.03.044.

[11] Kilic G. Using advanced NDT for historic buildings: Towards an integrated multidisciplinary health assessment strategy. J Cult Herit 2015;16:526–35. https://doi.org/10.1016/j.culher.2014.09.010.

[12] Historic England. 3D Laser Scanning for Heritage. 2018.

[13] Birtharia A, Jain SK. Application of ambient vibration testing: an overview. Int Res J Eng Technol 2015;02.

[14] Grujoska-Kuneska J, Jekic G, Shendova V. Comparative Analysis of Dynamic Characteristics of the St. Nikita Church. 19 Symp. MASE, Ohrid: 2022.